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Comparison of the use of life cycle assessment and ecological footprint methods for evaluating environmental performances in dairy production

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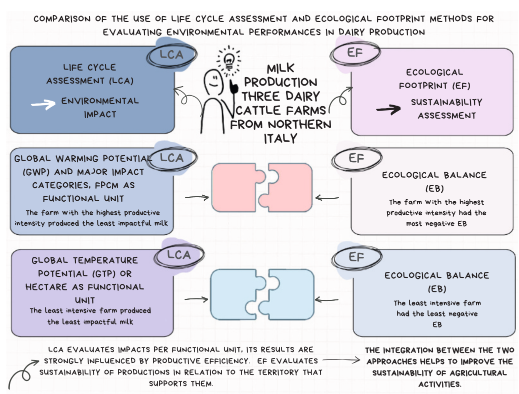
HIGHLIGHTS

- Ecological sustainability and environmental impact of milk were studied in three farms.
- Results from Life Cycle Assessment and Ecological footprint were compared.
- Results obtained with the two methods sensibly differed.
- Different metrics and functional units in Life Cycle Assessment analysis resulted in different rankings.
- Life Cycle Assessment and Ecological Footprint together enables a comprehensive assessment of environmental sustainability.

GRAPHICAL ABSTRACT



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ABSTRACT

One popular methodology for assessing the environmental impact of livestock sector is Life Cycle Assessment (LCA), that quantifies the environmental impact of a product. Ecological Footprint (EF) performs an environmental sustainability assessment, by comparing the demand for natural capital by an economic activity with the offer of such capital within a certain territory. The aim of the study was the comparison between LCA and EF in assessing the environmental performances of milk production, assuming as case study three cattle farms with increasing levels of production intensity. Different metrics and functional units (FU) (i.e., fat and protein corrected milk, FPCM and hectare) were adopted for LCA analysis, considering some of the major impact categories. For greenhouse gases emissions, the Global Warming Potential (GWP) and the Global Temperature Potential (GTP) were considered. Both metrics were calculated assuming or not the distinction between biogenic and fossil methane. Adopting GWP as a metric, the results per kg of FPCM provided by the LCA highlighted a different trade off compared to the EF method: the farm with the highest productive intensity produced the least impactful milk in terms of GWP but had the most negative Ecological Balance (EB). The same occurred for the other impact categories. When GTP was adopted, or the hectare was considered as FU, the least intensive farm, characterized by greater feed self-sufficiency, became the one that produced the least impactful milk and had the least negative EB. The study highlighted the scientific significance of the integration between the two approaches for creating a

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comprehensive representation of the effects of human activities on the environment. The LCA method evaluates impacts intensity referred to a specific functional unit and its results are strongly influenced by productive efficiency; the EF method evaluates environmental sustainability of productions in relation to the territory that supports them.

1. Introduction

The current global environmental situation calls for the development of methods useful for understanding the pressures of human activities on ecosystems. In this context, the agrifood systems plays an important role in terms of environmental impact: the share of agrifood system in total emissions in 2020 was 31 % (16 Gt CO_2 eq), with the most important contributors to global agrifood system CO_2 emissions from deforestation (2.9 Gt CO_2 eq) and CH_4 from enteric fermentation of ruminant livestock (2.8 Gt CO_2 eq), representing together nearly 40 % of the total (FAO, 2022). However, the agricultural sector has some unique characteristics that set it apart from all other human productive activities: firstly, it produces food for humans; secondly, it directly manages natural resources within agroecosystems providing and relying on ecosystem services (Garbach et al., 2014); finally, in terms of GHG, its emissions partly derive from atmospheric CO_2 fixed by plants in a biogenic cycle, meaning different warming potential of different sources of methane, considered in the Life Cycle Assessment (LCA). Methane from fossil fuel sources, indeed, has slightly higher emission values than those from biogenic sources (high confidence), as now accepted by IPCC (2021). Therefore, it is essential to pasy close attention to the selection of methodologies and indicators capable of assessing the effect of agricultural activities on ecosystems. LCA has become the recognized instrument to assess the ecological burdens and human health impacts connected with the complete lifecycle (creation, use, end-of-life) of products, processes and activities, enabling the assessor to model the entire system from which products are derived or in which processes and activities operate (Klöpffer et al., 2015). However, it only focuses on emissions and natural resource demand, without considering environmental availability of these. The Ecological Footprint (EF) method, on the other hand, allows for a direct comparison between natural capital demand and supply, establishing an ecological balance. However, none of the two methods allows to consider all the three pillars of sustainability (i.e., environmental, social, and economic dimensions), therefore the study only focused on the environmental point of view.

1.1. Life cycle assessment

LCA is an internationally recognized method, regulated by ISO standards and generally accepted for estimating the environmental impact of agricultural products from a global perspective. The European Commission, since 2003, identified LCA as the “best framework for assessing the potential environmental impacts of products” (European Commission, 2003).

In its broadest meaning, LCA incorporates into the analysis all the processes involved in product manufacturing throughout its life cycle, from raw material extraction to possible waste treatments. This method allows, starting from measured data or estimates, to calculate the impacts linked to an agricultural production process, considering not only what happens within the farm (e.g. methane emissions by animals) but also the impacts deriving from the production of all the inputs that enter the farm (e.g. purchased livestock feed, fertilizers, fuels) (Gislon et al., 2020). With the LCA approach a large number of environmental impact categories are analyzed at the same time, and the identification of the hotspots of the process is allowed, favoring the development of mitigation strategies.

In the livestock sector, LCA analysis gives the opportunity to understand where the production truly stands in terms of its environmental impact, but also what approaches can be implemented to reduce the impact in order to make livestock farming more sustainable. However, certain considerations must be taken, especially when it is used to make comparisons between different production systems. The choices about system boundaries, functional units and allocation methods are crucial and can significantly influence the results of the LCA assessment (Bava et al., 2018).

In addition, when performing LCA analysis it is important to pay attention in the selection of methodologies and metrics. In particular, since agricultural GHG emissions are dominated by short-lived climate pollutants, such as methane, there are ongoing discussions about the role of such short-lived greenhouse gasses, and about the associated metrics to be used in LCA studies, with significant implications for estimating the contribution of livestock farming to climate mitigation (Domínguez et al., 2021). In LCA studies, non-CO_2 emissions are commonly reported as ‘CO_2-equivalents’ and calculated using the Global Warming Potential (GWP) and 100-years is usually the time-horizon considered. The GWP metric assumes that any emission of any greenhouse gas, methane included, contributes to global warming in the same linear fashion. However, due to the short-lived character of methane, constant or decreasing methane emission rates would not induce additional global warming as the total stock of methane in the atmosphere would decrease (Lynch et al., 2020). For this reason, in order to account for the different behaviors of short-lived and long-lived greenhouse gasses, other metrics besides GWP were proposed to be used in LCA studies on agricultural production. GWP* became quite famous in the last few years, but it may also face some difficulties in implementation at national and project-levels, because it requires CH_4 emissions data both current and from the past 20 years, to estimate the warming effects (Cady, 2020; Costa Jr et al., 2021). Another metric suggested is the Global Temperature Potential (GTP). While the GWP is a measure of the heat absorbed over a given time period due to emissions of a gas, the GTP is a measure of the temperature change at the end of that time period (again, relative to CO_2) (EPA, Environmental Protection Agency, US, 2022). Moreover, the IPCC now accepts that different sources of methane have different warming potentials: methane from fossil fuel sources has slightly higher characterization factors than those from biogenic sources (Cave and Allen, 2021). This is largely due to the fact that the latter keeps the recycling between bio-system and atmosphere, while fossil fuel carbon is a “net” addition to the atmosphere, because burning fossil fuel releases this carbon (which had been stored underground for millions of years) at a much faster rate than it can be removed (Costa Jr et al., 2021). The choice of how to approach the sources of methane have different implications on LCA results and it is decisive if the analysis is used to determine optimal mitigation options.

1.2. Ecological footprint

Proposed by Rees in 1992 in the context of the debate on the notion of “carrying capacity” and developed by Wackernagel and Rees in the basic text of the methodology (1996), the EF is a simple and communicable indicator used to quantify the “total surface area of terrestrial and aquatic ecosystems necessary to supply all the resources and to absorb the emissions produced” (Passeri et al., 2013). It’s an environmental analysis methodology that makes it possible to carry out a ‘strong sustainability’ assessment, cohesive with the definition adopted in ecological economics, which provides for the conservation of natural capital and the impossibility of replacing it with economic capital (Barbier and Burgess, 2017). For this reason, it is a suitable tool in establishing an environmental sustainability condition; nevertheless, it should be considered that remaining within the carrying capacity is not a full requirement for sustainability (Galli et al., 2013). Indeed, as pointed out by Bastianoni et al., 2020, the EF is only able to ensure "a minimum but not sufficient condition" for sustainability considering that this indicator looks only at a quantitative balance of natural resources without investigating other aspects concerning qualitative implication or other ecological dimensions.

Precisely for this reason, it is a suitable tool for the assessment of environmental sustainability in the agricultural field, as this is an evaluation based on the comparison between consumption and availability of natural resources. Agriculture, together with other primary sectors (including fishing, forestry) differs from other productive activities for a specific reason, indeed it is the only sector characterized by the availability of natural resources. In fact, for firms in the agricultural sector, the natural capital appears in the balance sheet among the tangible fixed assets, explicitly named as "land" (Bruni and Franco, 2003).

The ecological balance (EB) is an environmental accounting tool, that can be applied at different levels, from global to regional (Franco, 2021), based on the comparison of two indicators: EF, on the demand side, which measures the ecological assets required to produce the used renewable resources and ecological services; Biocapacity, on the supply side, which tracks the ecological assets available and their capacity to produce renewable resources and ecological services. The result is expressed in a standardized unit called global hectare (gha), defined as follows: "*a hectare of biologically productive land or sea area with world average productivity in a given year*" (Wackernagel and Rees, 1996).

The main purpose of the method is to highlight the earth's ecological constraints, evaluating the pressure of economic activities on ecosystems (Goldfinger et al., 2014). The validity of this methodology for the agricultural sector, applied to crops as well as livestock, has been recognized internationally, as confirmed by the wide literature (Niccolucci et al., 2008; Mahdei et al., 2015; Li et al., 2020).

However, over the years, the EF has also received criticism. In an interesting article by Giampietro and Saltelli (2014) some aspects of the EF have been deeply discussed. In general, the biggest criticism raised against this method concerns the simplification of the calculations: it is emphasized how the EF approach "cannot capture a complex issue, such as the analysis of the sustainability of human progress" and how "gives comfortably low estimates of the level of overexploitation of natural resources".

Nevertheless, the aim of this approach is not to offer a total measure of sustainability, but rather to give relevant information for one particular aspect of sustainability that can enclose with a question: is the demand for natural resources by human activities supported by the capacity of terrestrial ecosystems to generate these resources?

1.3. Aim of the study

Despite their specific characteristics, both LCA and EF are methods suitable for evaluating the environmental performances of dairy farming. However, since they are based on different approaches, they may not necessarily provide unambiguous indications when applied to the same reality.

Moving from this assumption, this study focused on the comparison between the LCA and EF methodologies for assessing the effect of dairy production on ecosystems, by applying them to three dairy cattle farms as a case study. The objectives of the analysis were: (i) to verify if different approaches to environmental performance evaluation of agricultural activities provide similar results; (ii) to understand the causes of the possible differences, discussing strengths and weaknesses of the two methodologies; (iii) to draw general indications on the limits and potential of the two methods and their adequacy in providing a comprehensive representation of the environmental performances of dairy farming.

It should be specified that the theoretical comparison of the two methodologies goes beyond the scope of the study.

2. Material and methods

Three dairy cattle farms from the Po Plain (Northern Italy) were identified as a case study. This choice is justified by the fact that cattle farming, within animal production, is considered the major contributor to climate change due to the release of methane from enteric fermentation (Ripple et al., 2014). Moreover, among animal products, cow's milk is certainly the most studied in relation to its environmental impact, especially through the LCA method: several LCA studies have been performed in the past two decades to assess the global warming potential of cow milk production in both intensive and extensive systems and under both conventional and organic management (De Boer, 2003; Mazzetto et al., 2022).

The selected number of farms constituted a sufficiently useful test for our study, inasmuch were selected three farms representative of the dairy sector of the region in terms of land area, feed crop production, herd size and individual milk production. They were characterized by increasing size and intensity level both in terms of stocking density (LU/ha), individual milk yield (FPCM/cow) and milk production intensity per hectare. Moreover, they were all specialized dairy farms, dedicated all their land to the production of feed crops for cattle and did not sell any products other than milk and beef from cull cows and male calves for the veal industry. This sample of farms, having different characteristics for several aspects of the production process, is sufficient to appreciate peculiarities and differences among LCA and EF methods, representing the aim of the present study, rather than the evaluation of environmental impact of milk production itself.

2.1. Environmental impact assessment of milk production through LCA approach

An evaluation of the environmental impact of milk production was performed through the LCA method, structured following ISO 14040-compliant and ISO 14044-compliant LCA methodology (ISO 14040, 2006; ISO 14044, 2018).

2.1.1. Goal and scope definition

The goal of this LCA study was to quantify environmental impact assessment related to milk production, in the three case study farms. Environmental impact categories considered were: acidification, freshwater.

eutrophication, marine eutrophication, land use, resource use (fossils) and Global Warming Potential (GWP). Particularly, the Green House Gas (GHG) emissions were evaluated with different LCA metrics.

2.1.2. Functional unit, allocation, and system boundaries

One kilogram of Fat and Protein Corrected Milk (FPCM, 4.0 % fat and 3.3 % protein) was assumed as functional unit (FU). At farm level, the allocation was performed between milk and meat, using a physical method (IDF (International Dairy Federation), 2015). In addition, for the evaluation of GWP, the second functional unit was 1 ha of occupied area, which was adopted to estimate the environmental impact intensity on the land occupied by farms, for a better comparison with EF method. When occupied area was used as functional unit no allocation was performed at farm level.

An attributional approach, which considered from cradle to farm gate system boundaries, was adopted. Inputs (e.g., fuel, lubricants, electricity, organic and mineral fertilizers, pesticides, off farm feeds and bedding) and outputs (e.g., emissions to the air, milk, and meat) involved in the productive processes were considered (Fig. 1).

2.1.3. Life cycle inventory (LCI)

Primary data were collected by direct interviews of the farmer to gather information about farm characteristics, management, and

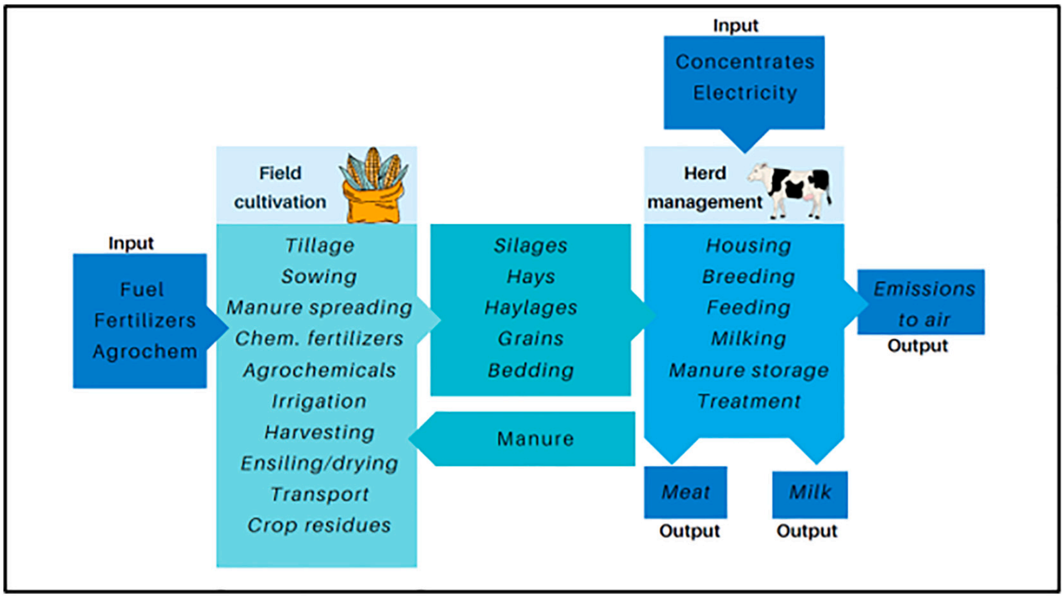

Fig. 1. From cradle to farm gate system boundaries considered in LCA analysis.

production: crop production for cattle feeding, livestock and manure management, purchased inputs (feed, fertilizers, pesticides, electricity, and fossil fuels), total amount and quality of milk and the number of animals sold per year.

The background data for the inputs production (e.g., bought-in feedstuffs), as well as for transport, were obtained from Ecoinvent version 3.8 (2021) and Agri-footprint version 6 (2022) databases, by considering allocation approach used by the databases themselves.

The three dairy farms chosen as case study were characterized by different stocking density, average daily milk production and production intensity (Table 1).

The dairy farms analyzed encompassed a wide range of farming size and production intensities: Farm 1 and 2 were characterized by high-intensive systems, with higher stocking densities (LU/ha), daily milk yield per cow and production intensity (kg FPCM/ha) compared to Farm 3. Farm 3 was much more self-sufficient in terms of animal feed and had a large area dedicated to perennial and multi-annual crops. On Farm 1, several forages were grown in the cultivated area, including maize (used as high moisture ear silage), Italian ryegrass, wheat, and sorghum. The grassland was represented by grass meadow and alfalfa. These forages were preserved and mainly used as silages in the cow rations. On Farm 2 the agricultural area was mainly cropped with maize, used in the cattle ration both as whole plant maize silage and high moisture ear maize. In addition, barley and soybean were grown, both preserved as silages. No agricultural area was dedicated to grassland. On Farm 3, most of the agricultural area was covered with perennial and multi-annual crops such as alfalfa and meadow. Italian ryegrass was also grown in a small area. All the forages were preserved as hay because the milk produced on the farm was used to make Parmigiano Reggiano PDO: in fact, the production regulations for this cheese prohibit the use of silage in the cows' diet.

All three farms purchased feed, mainly concentrates (both energy and protein rich). Soybean seeds and soybean meal were widely used as protein sources by all three farms, especially for lactating cow rations, as individual feed components or as ingredients in commercial feed.

2.1.4. *Emission estimation: GHG emissions on-farm*

All air emissions related to the milk production were calculated at farm level. Methane emissions from livestock enteric fermentation were estimated using the equation of Intergovernmental Panel on Climate Change guidelines (IPCC, 2019a). CH_4 emissions from manure storage were estimated using the method suggested by the IPCC (2019a). Volatile solid excretion was estimated considering the gross energy of the diets (kJ/kg of DM) evaluated using the equation of IPCC (2019a). For the feed digestibility (DE) values suggested by Product Category Rules of Grana Padano PDO (Castellani et al., 2015) were used. N_2O emissions from manure storages occurred in direct and indirect forms and they were estimated using the method from IPCC (2019a).

The effects on direct and indirect N_2O emissions derived by the application on the field of organic (solid and slurry) and inorganic fertilizers, as well as crop residues, were accounted for, using (IPCC, 2019b). CO_2 emissions occurring during field operations (i.e., plowing, harrowing, sowing, harvesting, and so on) were estimated using the processes of the Ecoinvent version 3.8 (2021) database. Emissions from livestock respiration were not accounted for.

For soybean meal and oil, direct Land Use Change (LUC) was included in the assessment; the method is described in detail in Rota et al. (2022).

More detailed information concerning the estimation of the on-farm emissions are reported in Rota et al. (2022).

2.1.5. *Emission estimation: other emissions on-farm*

The ammonia (NH_3) and nitrogen dioxide (NO_2) emissions that occur during animal housing, manure storage and spreading were estimated

Table 1
Main structural and productive data of the three case study farms.

Farm	Farm area	UAA[1]	LU[2]	Stocking density	FPCM[3]	Production intensity	Grassland[4]	Feed self-sufficiency[5]
	(ha)	*(ha)*	*(n.)*	*(LU/ha)*	*(kg/cow*day^{-1})*	*(kg FPCM/ha*y^{-1})*	*(%)*	*(%)*
Farm 1	183	177	627	3.7	33.7	26,098	49.2	46.6
Farm 2	48	46	169	3.5	27.8	22,095	0	59.4
Farm 3	89	87	215	2.5	25.1	13,663	94.3	73.8

[1] Utilized Agricultural Area; [2]Livestock units; [3]Fat and Protein Corrected Milk; [4]Grassland: including meadow and alfalfa UAA; [5]On ration dry matter.

according to the method proposed by the European Environment Agency (EEA (European Environment Agency), 2019a), based on the total amount of nitrogen excreted by the animals. The Tier 2 method uses a mass flow approach, based on the concept of a flow of total ammonia nitrogen through the manure management systems.

The NH_3-N and NO_2-N emission factors, as a proportion of total ammonia nitrogen, were specific for each manure type (slurry or solid) and each step in manure handling (EEA (European Environment Agency), 2019b). The NH_3 and NO_2 emitted during manure spreading and application of synthetic fertilizers were estimated following EEA (European Environment Agency) (2019a). The amount of N leached as NO_3 was estimated on the basis of N leached, following the IPCC (2019b) model. The amount of P lost in dissolved form to surface water (run-off) and leached was considered to estimate the transport to water of PO_4 as proposed by Nemecek et al. (2007).

2.1.6. Emission estimation: off farm processes

The emissions related to off farm activities were calculated using LCA software, Simapro PhD 9.4.0.2. The processes considered included the production chain of commercial feed (from crop growing to feed factory processing), production of purchased forages and bedding material, production of chemical fertilizers, pesticides, diesel, and electricity used in the farms. Transportation was accounted for feed and bedding materials.

2.1.7. Life cycle impact assessment (LCIA)

After classification, characterization was performed with different methods, depending on the environmental impact categories considered in the LCA. For the emission of GHG, characterization was performed through different methods implemented in the latest version of Simapro Software, to compare results obtained with different characterization methods.

The metrics used were GWP and GTP, both 100-year time horizon, with or without considering the differences between biogenic and fossil methane. For GWP, when the differences between the origins of methane were taken into account (GWPbm), characterization factors of 27.2 and 29.8 were considered for biogenic and fossil methane, respectively. Similarly, for GTP, when the different origins of methane were considered (GTPbm), characterization factors of 4.7 and 7.5 were applied for biogenic and fossil methane, respectively. When no differences in the origin of methane were taken into account, characterization factors of 29.8 and 7.5 were used for methane for GWP and GTP, respectively.

For the other impact categories considered, i.e., acidification, freshwater eutrophication, marine eutrophication, land use, resource use (fossils) it was used the EF 3.0 Method (adapted) V1.03.

The LCIA was performed by using the software Simapro PhD 9.4.0.2.

2.2. Environmental sustainability assessment of milk production with the EF approach

The evaluation of milk production environmental sustainability carried out within the EF approach is based on the comparison between the carrying capacity of the farming systems and the impact of production activity. This process is structured into the assessment of three indicators:

1. BC (Biocapacity), which expresses the availability of natural resources;
2. EF (Ecological Footprint), which expresses the use (impact) of natural resources;
3. EB (Ecological Balance) = BC – EF.

2.2.1. Data source

The analysis was based on primary data collected through direct interviews. The requested information can be divided into three categories:

1. bioproductive surfaces: hectares of forest land, grazing land, water, and built-up land;
2. cropland: agricultural areas used (with the specification of crop type), inputs used (fertilizers, pesticides, electricity, water, machine and labor hours);
3. livestock: number of heads with the category distinguished into dairy cows, dry cows, calves, and management of animals.

2.2.2. Goal and scope definition

The main objective was to verify the environmental sustainability for milk production in the same three farms used for the LCA analysis and to compare the results obtained.

2.2.3. Functional unit

The functional unit used was the global hectares (gha), which represents a standardized hectare with world average productivity. The factors used to convert the hectares of different land types into their equivalent global hectares were yield factor (YF) and equivalence factor (EQF). The yield factor is a measure of a biologically productive area in a given country compared to the global average productivity of the same land type. Equivalence Factors convert specific world average land area, such as cropland or forest, into global hectares. The conversion factors were extracted from the Global Footprint Network database (GFN, 2023).

2.2.4. Biocapacity

Biocapacity represents the availability of natural resources, and it is measured considering five major land cover. The first one is the cropland, which is destined for field cultivation and originates a biocapacity (BC_{FC}). The other four typologies, which at farm level all contribute to generate a not productive areas biocapacity (BC_{NP}), are forest land, grazing land, built-up land and water (Fig. 2). BC_{FC} is calculated as the sum of the biocapacity of all crops in the farming system. The biocapacity of each crop is obtained as proposed by EF base methodology (Wackernagel and Rees, 1996). The total value was calculated from the contribution of each crop (i) considering its area (A_i), the yield factor YF_i, defined as the ratio of the average farm yield (Y_{Fi}) and the world yield (Y_{Wi}), which value is available in the FAOSTAT database (FAO, 2022), and then the EQF.

$$BC_{FC} = \sum_i (A_i \text{ x } Y_{Fi}/Y_{Wi} \text{ x } EQF).$$

For the other four typologies of land cover, as explained by Wackernagel and Rees (1996), the calculation of BC is based on the transformation of each bioproductive area into global hectares by multiplying its dimension (A) for the country's specific yield factor (YF) and the equivalence factor (EQF). It follows that BC_{NP} is calculated as the sum of the four BC associated to forest land (F), grazing land (G), built-up land (B) and water (W):

$$BC_{NP} = (A_F \text{ x } YF_F + A_G \text{ x } YF_G + A_B \text{ x } YF_B + A_W \text{ x } YF_W) \text{ x } EQF.$$

The total biocapacity is represented by the sum of the two components: $BC_{TOT} = BC_{FC} + BC_{NP}$.

2.2.5. Ecological footprint

The use of natural resources linked to farm management (Fig. 2) is expressed by the sum of ecological footprints originated by fields cultivation (EF_{FC}) and herd management (EF_{HM}):

$$EF_{TOT} = EF_{FC} + EF_{HM}.$$

To evaluate the EF of croplands it is possible to refer to the methodology conducted by Passeri et al. (2013), which is considered the sum

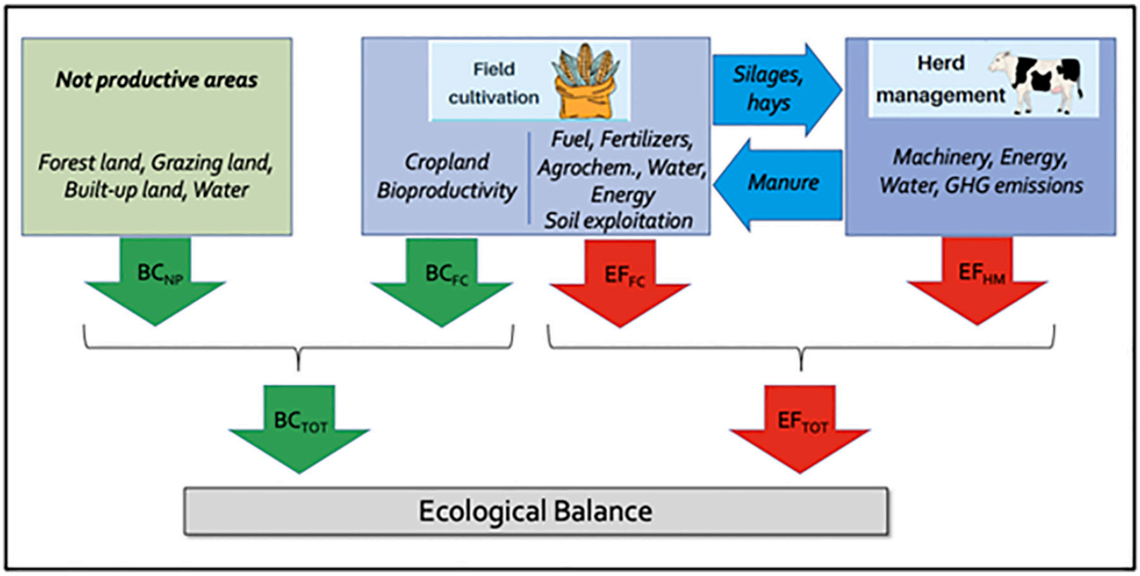

Fig. 2. The evaluation process considered in the analysis. BC_{NP} = Biocapacity for not productive areas; BC_{FC} = Biocapacity for field cultivation; EF_{FC} = Ecological footprints originated by fields cultivation; EF_{HM} = Ecological footprints originated by herd management.

of two components:

- EF_{INP}, i.e. the inputs used in the production process such as fuel consumption, energy for irrigation, use of fertilizers and pesticides, and work.
- EF_{OVP}, i.e. overproduction, which identifies the difference between what the crop produces under natural conditions and what it produces under human pressure (for example, by using fertilizer).

The EF_{INP} and EF_{OVP} are evaluated for each crop present and at the end are added to have the total value.

The evaluation of livestock instead, looks to the following principal impact: animals GHG emissions, fuel consumption, energy, work employment.

Concerning the impact of GHG emissions, the values of per head CH_4 and N_2O emissions, due to enteric fermentation and manure management, associated to the different categories of cows (lactating cows, dry cows, heifers, and young calves) were expressed in carbon dioxide equivalent emissions (CO_2-eq). Then, the total CO_2-eq emissions were converted in terms of EF according to the coefficient proposed by Mancini et al. (2016).

Detailed information about the calculation of EF_{INP}, EF_{OVP} and EF generated by other sources of impact can be found in several articles (Kitzes et al., 2008; Blasi et al., 2016; Franco, 2021; Martella et al., 2023).

2.2.6. Ecological balance

Once obtained EF_{TOT} and BC_{TOT}, the difference between the two values expresses the EB whose result highlights the situation of environmental sustainability, with a positive result, or unsustainability, with a negative result, of the production system analyzed.

For this study, the EB assessment was carried out using a calculation model implemented on Microsoft Excel and developed by the research group at the University of Tuscia.

3. Results

3.1. LCA results

3.1.1. GWP and GTP

Table 2 shows the results of LCA analyses on the global warming impact of milk production using different metrics: GWP and GTP, which do not consider the differences between biogenic and fossil methane; GWPbm and GTPbm, which evaluate biogenic methane differently from fossil methane.

Table 2
Global warming metrics of milk production from LCA analysis.

	Unit	GWP[1]	GWPbm[2]	GTP[1]	GTP bm[2]
FU[3]: kg FPCM[4]					
Farm 1	*kg CO_2eq*	1.68	1.59	0.87	0.78
Farm 2	*kg CO_2eq*	1.77	1.68	0.96	0.86
Farm 3	*kg CO_2eq*	1.85	1.74	0.85	0.73
FU[3]: ha					
Farm 1	*ton CO_2eq*	50.3	47.6	26.1	23.2
Farm 2	*ton CO_2eq*	48.3	45.9	26.1	23.5
Farm 3	*ton CO_2eq*	28.0	26.4	12.9	11.1

[1] Without considering the differences between biogenic and fossil methane; [2]Considering the differences between biogenic and fossil methane; [3]Functional Unit; [4]Fat and Protein Corrected Milk.

If referred to the kg of FPCM, when the differences between biogenic and fossil methane were not considered, GWP values, were inversely related to stocking density (LU/ha), milk yield per head (kg/cow*day^{-1}) and production intensity (kg FPCM/ha*y^{-1}) of the farms (Table 1). The highest impact per kg FPCM was estimated on Farm 3, the least intensive with the lowest milk production per head and per hectare, and the lowest value was for Farm 1, which had the highest milk production. When the differences between biogenic and fossil methane were taken into account, the values decreased, but the ranking of the farms in terms of GWPbm of milk production did not change, compared to GWP. On the other hand, the GTP metrics showed different trends. The GTP per kg FPCM was lower on Farm 3, which had lower milk production per head and per hectare compared to the other two farms. Taking into account the differences between fossil and biogenic methane, GTPbm showed a reduction in impacts per kg of milk compared to GTP, but the ranking of the farms did not change.

Considering the land (ha) as FU, the ranking of farms is the same obtained with the GTP metrics referred to FPCM. For all the metrics used for estimating GHG emissions per ha, indeed, the lowest values were obtained in Farm 3 (Table 2), which had lower milk production per head and per hectare, compared to the other two farms (Table 1). In this sense, GHG emissions per unit of land, were directly related to stocking density (LU/ha), milk yield per head (kg/cow*day^{-1}) and production intensity (kg FPCM/ha*y^{-1}) of the farms (Table 1).

In Fig. 3, the different contributions to GWPbm and GTPbm (both referred to kg of FPCM as FU) of emissions from fossil and biogenic sources, and from land transformation are shown. With both metrics the differences between biogenic and fossil methane were accounted for.

The biogenic contribution to GWPbm was very large in comparison to fossil and land transformation sources (Fig. 3A), while the opposite was obtained for the GTPbm (Fig. 3B).

In the case of GWPbm for all the studied farms, the greatest contribution came from biogenic sources (on average 60 %), mainly represented by enteric fermentation and manure storage (53.3 and 46.5 %, on average, respectively). Biogenic emissions were particularly high on Farm 3, where land transformation was low. The main contributors to land transformation and fossil emissions for all three farms were on-farm crop production and purchased feed (both energy and protein feed).

When considering GTPbm, the greatest percentage contribution to emissions for all three farms came from fossil sources (on average 52 %). For Farm 3, the contribution of biogenic GTPbm was higher than that of land transformation (27 % vs 16 %, respectively); the opposite occurred for Farm 2, where the contribution from land transformation was higher than that of biogenic sources (39 % vs 19 %, respectively). For Farm 1, similar contributions were derived by land transformation and biogenic sources (23 % and 21 %, respectively). Purchased protein feeds were by far the most important source of GTPbm for land transformation for all the studied farms, accounting for more than 90 % on average.

3.1.2. Other LCA impact categories

The results of the other impact categories considered are shown in Table 3.

As for GWP and GWPbm, Farm 1 had the lowest values, while Farm 3 had the highest values, for all the impact categories. This highlights, for also this other impact categories, the same relationship found with GWP, when unit of product is considered as FU, i.e., a negative relationship between environmental impact and stocking density (LU/ha), milk yield per head (kg/cow*day^{-1}) and production intensity (kg FPCM/ha*y^{-1}) of the farms (Table 1). An exception was detected for the use of resources (fossil), due to the fact that the high level of production of Farm 1, probably, led a dilution effect of most of the impact categories, but also to a wider use of agricultural machinery. For resource use (fossil) the lowest impact was reached by Farm 3, that was also the farm with the lowest value of GTP (Table 2), suggesting a limited use of fossil methane as source of energy.

3.2. EF results

Table 4 shows the single components of BC and EF for each farm. It emerges that the total value of EF ($EF_{FC} + EF_{HM}$) was equal to 1935.75 for Farm 1, 297.26 for Farm 2 and 686.22 for Farm 3. On the other hand, the total value of BC ($BC_{FC} + BC_{NP}$) was 1094.62 for Farm 1, 103.38 for Farm 2 and 573.51 for Farm 3. The difference between EF and BC gives the EB which values, together with the related EF and BC, are shown in Fig. 4. The fact that EB was always negative implies that all farming systems were not sustainable with an EF > BC. This is not surprising, considering the density of cows (higher than 3 heads/ha), a factor that increases the EF indicator, and the scarce presence of bioproductive areas (elements of biocapacity), which makes it difficult to offset the impact generated by livestock.

The results suggest some observations related to the two indicators BC_{TOT} and EF_{TOT}. With regard to the composition of the BC, the main contribution for each farm came mainly from cultivated land. In fact, the percentage of BC deriving from crops was respectively 99 % for Farm 1, 96 % for Farm 2 and 99 % for Farm 3. Differences emerged regarding the composition of EF. While for Farm 1 and Farm 3 the main impact derived from the same crops with a percentage of 66 % for both, for Farm 2 instead it was the value of the livestock that had a greater impact (58 %) than the crops (42 %).

To compare the environmental results of the three production systems, it is necessary to define indices that make the balances of the respective ecological balances comparable. For this purpose, it is possible to divide the EB value by the number of hectares and calculate an environmental performance index, obtaining the values of the unitary balance. Although all three farms were unsustainable from an environmental point of view, Farm 1 appeared to be the one with the more penalizing values. This means that the farming systems with a higher rate of resource utilization were the ones more unsustainable (Farm 1), with an EB equal to −841 gha.

The results at both global and unitary level are reported in Fig. 4, where the supply of natural resources associated with the BC is colored in green, while the resource impact associated with the EF indicator is represented in red. Their difference shows an unsustainable environmental situation representing the EB (dark grey). In the figure, these three indicators are represented referring to the values of the scale on the left axis.

However, the most important outcome of the study is the unitary EB, which in the figure is colored in light grey and refers to the scale values placed on the right axis. On the basis of such indicator, the assessment and subsequent comparison with LCA results were made.

3.3. Comparison between the two methods

By comparing results obtained with the two different methods (Table 5) it is possible to notice that, when the most well-known and widely used metric (GWP) and functional unit (kg FPCM) in LCA evaluations of carbon footprint was used, the LCA method highlighted a different trade off compared to the EF method. Farm 1 had the lowest

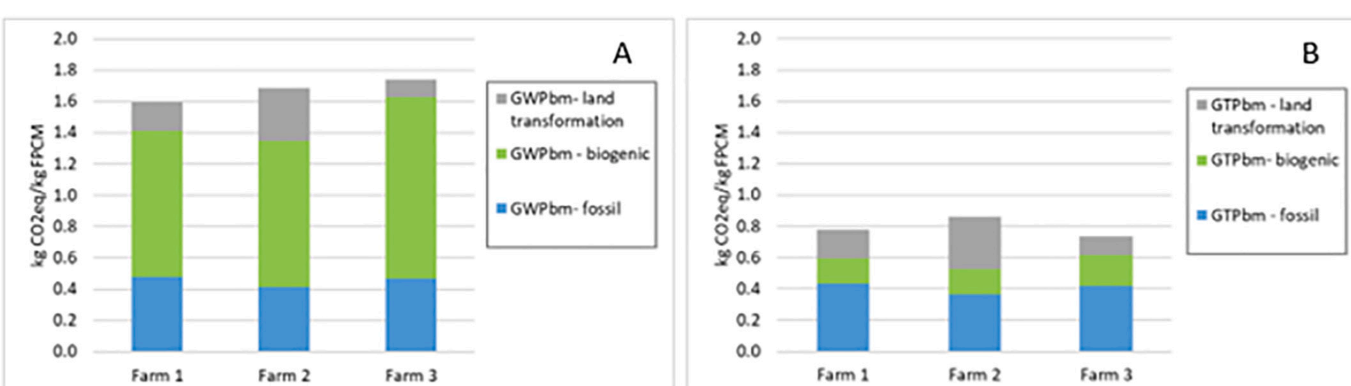

Fig. 3. The GWPbm (A) and GTPbm (B) values for milk production in the three case study farms calculated by considering the differences between biogenic and fossil methane.

Table 3
Other impact categories of LCA analysis (expressed per kg of FPCM, Fat and Protein Corrected Milk).

Impact category	Acidification	Eutrophication, freshwater	Eutrophication, marine	Land use	Resource use, fossils
	mol H+ eq/ kg FPCM[1]	*kg P eq/ kg FPCM*[1]	*kg N eq/ kg FPCM*[1]	*Pt/ kg FPCM*[1]	*MJ/ kg FPCM*[1]
Farm 1	0.028	0.0001	0.007	50.3	3.35
Farm 2	0.030	0.0002	0.008	72.8	2.91
Farm 3	0.038	0.0001	0.009	74.7	2.78

[1] Fat and Protein Corrected Milk.

Table 4
Composition of Biocapacity (BC) and Ecological Footprint (EF).

Farm	Field cultivation		Herd management	Not productive areas
	BC_{FC}[1] *(gha)*	EF^{2}_{FC} *(gha)*	EF^{3}_{HM} *(gha)*	BC^{4}_{NP} *(gha)*
Farm 1	1086.34	1293.84	641.91	8.28
Farm 2	99.49	124.13	173.13	3.89
Farm 3	570.66	454.72	231.50	2.85

[1] Biocapacity for field cultivation; [2]Ecological footprints originated by fields cultivation; [3]Ecological footprints originated by herd management; [4]Biocapacity for not productive areas.

environmental impact in terms of GWP per kg FPCM according to the LCA methodology, but was the least environmental sustainable according to the EF methodology. The opposite is true for Farm 3. However, when considering the impact in terms of GTP, the result of the comparison changed: in this case, Farm 3 produced the least impacting milk and also had the least negative balance in terms of EF. Same results occurred when GHG were referred to the unit of land, highlighting in this sense a greater point of contact between the two methods, as for GTP metric.

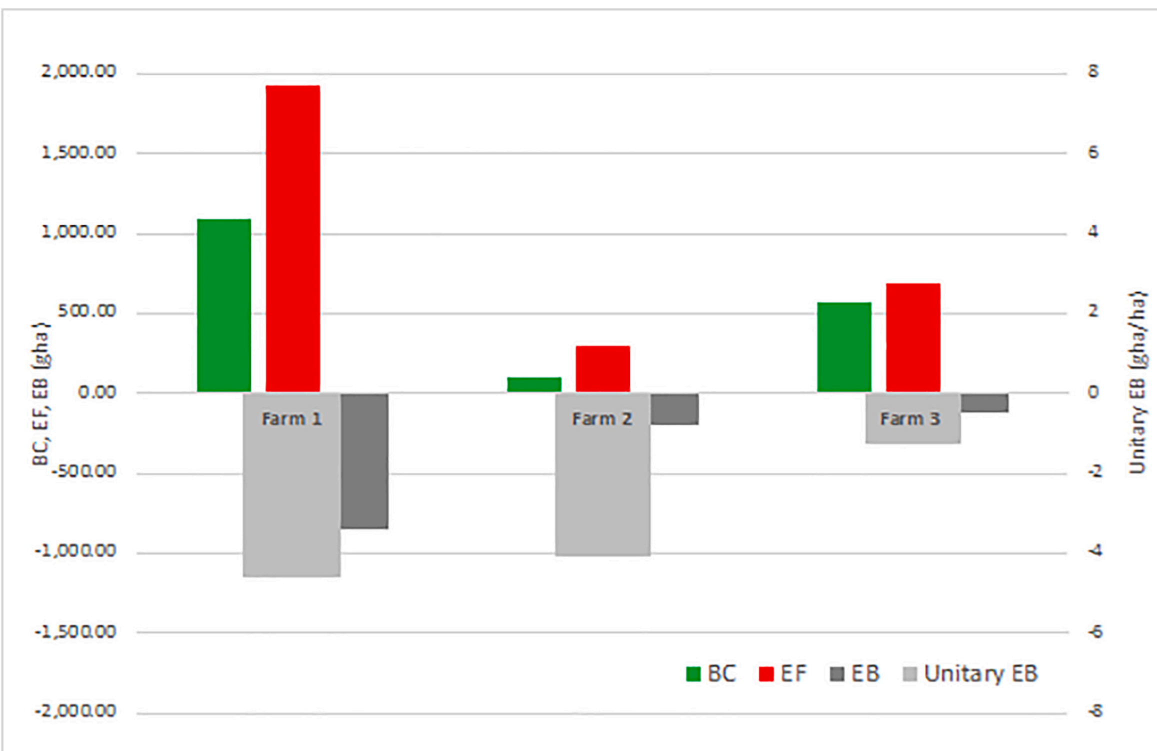

Fig. 4. Representation of Ecological Balance. BC=Biocapacity; EF = Ecological Footprints; EB = Ecological Balance.

Table 5
Comparison between the environmental performances of the three case study farms using the two methods.

Farm	LCA				EF
	GWPbm[1] *(kg CO₂ eq/kg FPCM)*	GTPbm[1] *(kg CO₂ eq/kg FPCM)*	GWPbm[1] *(kg CO₂ eq/ha)*	GTPbm[1] *(kg CO₂ eq/ha)*	Unitary Balance *(gha/ha)*
Farm 1	1.59	0.78	47.6	23.2	- 4.53
Farm 2	1.68	0.86	45.9	23.5	- 4.01
Farm 3	1.74	0.73	26.4	11.1	- 1.26

Note: red: worst values; orange: intermediate values; green: best values.
[1]Considering the differences between biogenic and fossil methane.

4. Discussion

4.1. LCA

Results for GWP of cow milk production obtained in the present study are consistent with the results reported in other studies of the international literature (e.g., Pirlo and Lolli, 2019; Gislon et al., 2020), with regard to the relative values, highlighting the fact that LCA method is able to enhance the managerial differences of livestock production systems, in terms of environmental impact. As for the present study, indeed, Pirlo and Lolli, 2019) and Gislon et al. (2020) found higher environmental impact per kg of product, for less intensive farms, compared to more intensive farms. The three farms varied in size, intensity, and feed self-sufficiency level, which, as said, affected their impact per kg of milk. As stocking density, individual milk production and production intensity increased, the GWP per kg of milk decreased. From LCA analyses on dairy production, the average milk production level emerged as one of the most important factors in influencing GWP of milk (Guerci et al., 2013a). As individual milk production increases, the environmental cost of the animal maintenance, both during the unproductive periods (heifer raising and dry period) and during the lactation period, is divided over a greater number of kg of milk. The same relationship is valid for most of the other impact categories that could be included in a LCA analysis. Nevertheless, the results are controversial in regard to the fossil resource use, lowest for the least intensive farm (Farm 3) considering the unit of product. Cederberg and Mattsson (2000) and Guerci et al. (2013b) also found lower emissions per kilogram of milk, when the dairy system was characterized by a reduced use of fossil fuels for crop growth.

In terms of absolute values, results obtained for GWP (either by considering or not biogenic distinction) may be evaluated as higher when compared to the literature (e.g., Gislon et al., 2020), depending on the environmental load of soybean and the emission factors proposed by the most recent IPCC guidelines (2019ab) implemented in the present study.

As expected, if land was considered as functional unit, the ranking of the three farms was the opposite, with the least intensive showing lowest values for climate change, calculated with GWP metrics, and most of the other impact categories analyzed. These results are consistent with the international bibliography (e.g., Pirlo and Lolli, 2019; Berton et al., 2021), which impressively documents that if the unit of product is considered for referring the environmental impact, intensive dairy systems result to be more sustainable, while, on the contrary, by using farm area as reference for environmental impact, extensive dairy systems result to be more environmentally sustainable.

Productive land is a limited resource, therefore, the inclusion of an area-based FU adds an important dimension to the assessment of the impacts of extensive, dairy systems (Berton et al., 2021). As stated by Ross et al. (2017), LCA studies using kg of milk as the sole FU of the dairy farm fail to grasp the complexity of dairy systems, and to do so requires the inclusion also of productive land as an FU. Acidifying and eutrophying emissions, for instance, are mostly local phenomena, which cannot be indexed by the unit of milk (Potting and Hauschild, 2006).

However, there are uncertainties in the use of area-based FU with LCA, since the comparison between different dairy farms should be done on the amount of milk produced, otherwise the risk is to favor less productive systems, with consequences on economic sustainability and on the supply of products.

Generally speaking, a reduction of production per hectare means, on a global scale, growing more land to have the same amount of food, by subtracting further spaces to natural habitat. This contradiction can be overcome by adopting, together with LCA, the EF approach. The latter, indeed, is able to performs an environmental sustainability assessment, not by only considering the pressure on a certain land, but by comparing the demand for natural capital by an economic activity with the offer of such capital within a certain territory.

The relative contribution of biogenic emissions (methane from enteric fermentation and manure storage) to the GWP per kg of milk was the majority in all the three farms. The relative contribution of biogenic methane was high in the least intensive farm, mainly due to the low contribution of emissions from land transformation (Fig. 3).

From the analysis of the percentage contribution of different processes to GWP per kg FPCM, it emerged that in all the three farms the major contributor to GWP from fossil sources was on-farm crop production (fuel for field operation, production and spread of fertilizers and pesticides etc.). Protein feed purchased were by far the most important sources of GWP from land transformation, for all the studied farms. The quite high contribution of land transformation on the total CO_2 equivalents, for all the farms but especially for Farm 2 (Fig. 3), suggested the importance of purchased feed origin (mainly soybean meal) in terms of environmental impact when LCA method was applied.

Differentiating between biogenic and fossil methane slightly reduced milk GWP, due to the lower characterization factor of biogenic methane in comparison to fossil one. However, the trend of environmental impact of the milk from the three farms remained the same, both considering FPCM or ha as functional unit (Table 2).

Using a different metric such as GTP allows for the resizing of the weight of methane, both biogenic and fossil. In this case, the ranking of the three farms in terms of impact per kg of milk changed and the farm with the least production intensity became the one with the least impacting milk (Table 2). Using GTP, the intensity and efficiency of milk production lose importance and feed self-sufficiency becomes more important as it helps to keep emissions from fossil sources and from land transformation low. The latter are largely linked to the purchase of external feed (especially soy). By attributing different coefficients to biogenic and fossil methane in the calculation, all GTP values were lowered and the differences between the impacts of milk produced on the three farms were deepened (Table 2). The results obtained for GTP were comparable to those reported by Reisinger et al. (2017), namely 0.48–0.51 kg CO_2eq/kg FPCM (excluding climate-carbon cycle feedbacks), although the results obtained in this study were slightly higher.

4.2. EF

All farms had a negative EB and, consequently, can be identified as environmentally unsustainable production systems. In all cases, in fact, the availability of resources, given by the positive balance of crops and non-productive surfaces, failed to compensate for the impact generated by livestock. In fact, it should be noted that, albeit with difference, the impact of livestock was consistent in all three farms and added to the impact by the crops, it generated an EF value higher than BC and consequently a negative EB in all three farms. To this, we must consider the scarce presence, for all three systems analyzed, of non-cultivable surfaces, which increased the value of BC, and in particular of forest land, considered a fundamental source of absorption for the storage of carbon deriving from CO_2-eq emissions. One consideration must be done for the impact of livestock. As already emerged in various studies (Lovett et al., 2006; Black et al., 2021) and as confirmed also in our study, dairy systems generate large quantities of emissions mainly related to animals' enteric fermentation and manure management (CH_4 and N_2O emissions). Clearly, we are talking about factors that significantly contribute to global warming, a subject of continuous debate that requires the implementation of good agricultural practices and the use of reduction tools (Coderoni et al., 2013). This is a fundamental element of analysis for the EF, as the quantities of emissions of CH_4 and N_2O increase in proportion to the amount of livestock, thus a reduction of the number of heads could be an improvement.

Our results find some similarities with another study conducted for the agricultural system of Viterbo (Franco, 2021), but with a completely opposite result of the EB. Also in that case, the BC derived mainly from crops representing around 78 % with an impact of 68 % greater than that of livestock 31 %. However, the value of the EB of the entire system was positive, as the croplands were joined by non-cultivable surfaces, thus defining the system in a condition of environmental sustainability, offsetting the impact deriving from livestock. This result is justified by the fact that the agricultural system of Viterbo was characterized by extensive systems with a greater presence of crops rather than livestock.

In this study, on the contrary, the value of the EB assumed a negative value for each farm, establishing a condition of unsustainability, in terms of environmental point of view. This means that the 'carrying capacity' of the single system, in this case, is not able to support the different activities carried out. The result is nothing new considering that Lombardy is in first place in Italy for the size of the cattle population and the only region in which the impact of the livestock sector consistently exceeds the biocapacity of the entire agricultural sector, affecting that offered by the region itself (Franco, 2020).

Although the EF has not been used for an evaluation in the milk production process, and therefore this study is configured as the first in this sector, in the literature it is possible to find some evaluations that use this approach relating to the agricultural sector, and which concern both individual products and supply chains (Martella et al.2023, Biagetti et al., 2023).

What is important to highlight is that the various information that the model can provide assumes the function of guidelines to be followed to improve the situation, promoting targeted modifications to certain production techniques. All are aimed at reducing the level of environmental impact.

4.3. Comparison between the two methods

By comparing the results obtained with the two different methods (LCA and EF) it is possible to notice that when the most well-known and widely used metric and functional unit in LCA evaluations of carbon footprint (GWP) was used, the LCA method highlighted a different trade off compared to the EF method (Table 5). The two methodologies (LCA and EF), indeed, refer to distinct visions of the relationship between agriculture and environment, suggesting a useful synergy of the two methods.

The LCA method looks at the impact assessment in terms of production efficiency and, therefore, with the typical approach of environmental economics. Therefore, an increase in the environmental impact that determines a more than proportional increase in production efficiency improves environmental performance. This condition translates into the possibility of pursuing the goal of the so-called "sustainable intensification", where this term means an increase in production efficiency which is accompanied by a reduction in environmental impact for unit of product (Petersen and Snapp, 2015).

The EF method, on the other hand, looks at the assessment of sustainability in terms of maintaining natural capital. In these terms, an increase in the environmental impact, regardless of its effect on production efficiency, always determines a worsening of environmental performance at a farm level. It follows, in the perspective that refers to the ecological economy paradigm, that sustainable intensification is, by definition, theoretically impossible. On the other hand, in a global perspective of the environmental cost of food production, the most efficient production processes allow for the same productions to be obtained with a lower environmental cost (Mahon et al., 2017).

However, results obtained with LCA by using GTP metric or by using the unit of area as functional unit seem to be closer to those calculated with EF method. By using GTP the ranking of the three farms in terms of impact per kg milk changed compared to GWP and the farm characterized by the least production intensity became that with the least impacting milk (Table 5). This partially depends on the fact that the percentage of biogenic methane was higher in Farm 3 and, in calculating the GTP, the coefficients assigned to biogenic and fossil methane are significantly different (Fig. 3). Moreover, when it comes to GTP, the intensity of milk production became less significant while feed self-sufficiency gained importance as it helped to reduce fossil and land transformation emissions, which were largely associated with the purchase of external feed (especially soy). Land transformation largely contributed to the total CO_2 equivalents, especially in Farm 2 (Fig. 3). The lack of using area-based FU with LCA, making an impartial comparison between different productive systems, may be filled by using LCA method together with EF.

Strengths and weaknesses of the two different approaches.

The two methods look at different evaluations. LCA is a methodology that quantifies the environmental impacts intensity, either on a unit of product or on a unit of land; on the contrary, the EF evaluates the environmental sustainability of economic activities carried out in a specific area. Although these are tools that can provide useful information to introduce actions aimed at reducing or compensating for the environmental implications, they have limits that must be considered.

Table 6 presents a list of strengths and weaknesses for the two methodologies obtained either from the results of the present study and arguments that go beyond the scope of the study.

This information is useful for understanding how to refine the methods and provide a more robust assessment of the implications of agricultural activities. The LCA method generally allows to quantify many impact categories at the same time whereas EF has a limited scope, focusing mainly on land use and carbon emissions. Moreover, the LCA method is widely recognized and used in both industry and academia, which can help to promote a common understanding of environmental performance metrics. Unfortunately, LCA is data- and resource-intensive, and can be complex to interpret and communicate to non-expert audiences. Conversely, EF provides a simple, easy-to-understand metric for measuring the environmental sustainability of a process. Moreover, LCA does not take into account the resources available at the local level but detaches the production process from the territory. Conversely, the EF method does not consider the process efficiency and the need to produce food for humans. As highlighted by the results obtained in the present study, results of LCA are affected by some crucial methodological choices, first of all, the functional unit, while EF is related to weak data basis. Both tools lack estimates for certain sustainability elements and could hence complement each other.

Table 6
List of strengths and weaknesses of Life Cycle Assessment (LCA) and Ecological Footprint (EF) methods.

	Strengths	Weaknesses
LCA	- Quantified environmental impacts per kg of product - Identification of possible shifts and trade-offs among different productive sectors - Identification of hotspots of the production processes to help develop mitigation strategies - Evaluation of different source of methane (biogenic vs fossil) when evaluating carbon footprint environmental impact category - Comparison between different farming system based on unit of product - Focus on production process	- Ecological sustainability not evaluated - Results affected by some crucial methodological choices (e.g. functional unit) - Ecosystem services and other aspects not evaluated - It does not consider the resources available at the local level
EF	- Applicability of the agricultural sector - Synthetic indicator easy to understand - Ecological sustainability assessment calculation - Applicability to different levels - Focus on local resources	- Simplification in calculations - Availability of data - Weak data basis

5. Conclusions

The comparison between LCA analysis and EF highlighted deep differences in the evaluation of the environmental performances of cow milk production in three Italian dairy cattle farms, especially when GWP and the unit of product were used as the reference for Life Cycle Assessment. The environmental performance ranking of the three farms highlighted a different trade off considered by the two methods, when corrected milk was used as functional unit. However, the comparison highlighted how the most recent development in LCA for assessing greenhouse gases emissions, such as the adoption of GTP instead of GWP, allows in some cases to obtain results more consistent with the indication provided by the EF. Another point of contact between the two methods is when unit of area was used for referring LCA environmental impact, even though the latter still evaluating environmental sustainability as impact intensities. In addition, the evaluation of different environmental impact categories, together with carbon footprint, may allow to have an integral element of a wider life cycle sustainability assessment, when using LCA.

Both methods have strengths and weaknesses: LCA has the limit of measuring only the impacts of a process and not the environmental sustainability in a broad sense. It does not take into account the resources available at the local level but detaches the production process from the territory. Conversely, the EF method has a territorial perspective, but it is less suitable for a farm-level view. Moreover, it does not take into account the efficiency of the production process.

The evaluation of the environmental performances of milk production, as well as other agricultural and livestock productions, requires multidimensional and particularly careful approaches considering the special role of agriculture as a source of food for humanity and an activity that manages agro-ecosystems. In this sense, the integration between multiple approaches and visions can help to create a more comprehensive and nuanced representation of the effects of human activities on the environment for an adequate support to agricultural policies. Open and non-ideological comparison between different approaches used by researchers who focus on a common goal to create a virtuous discussion is useful and desirable.

CRediT authorship contribution statement

E. Biagetti: Data curation, Formal analysis, Software, Writing – original draft. **G. Gislon:** Data curation, Formal analysis, Software, Writing – original draft. **A. Martella:** Data curation, Formal analysis, Software. **M. Zucali:** Data curation, Formal analysis, Software, Writing – review & editing. **L. Bava:** Data curation, Formal analysis, Software, Writing – review & editing. **S. Franco:** Conceptualization, Investigation, Methodology, Project administration, Supervision, Writing – review & editing. **A. Sandrucci:** Conceptualization, Investigation, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data availability

Data will be made available on request.

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